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Development of Composite Coiled Tubing for Oilfield Services

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Abstract

As coiled tubing services expand to meet the challenges of the oil and gas industry, limitations of steel tubulars continue to temper the potential impact of this workover service. Presently, coiled tubing used in well servicing operations is milled from modified A-606 High Strength Low Alloy (HSLA) steel, with yield strengths ranging from 70 ksi to 100 ksi. Although current coiled tubing services can performed saf ly and reliably with conventional steel coiled tubing, the behavior of the isotropic metal limits the yield pressure and tensile load capability of the tube.

Composite Coiled Tubing (CCT) offers the potential to exceed the performance limitations of isotropic metals, thereby increasing the service life of the pipe and extending perational parameters. CCT is constructed as a continuous tube fabricated from non-metallic materials to provide high body strength and wear resistance. CCT can be tailored to exhibit unique anisotropic characteristics which optimally address burst and collapse pressures, tensile and compression loads, as well as high strains imposed by bending. This enabling capability expands the performance parameters beyond the physical limitations of steel or alternative isotropic material tubulars. In addition, the fibers and resins used in CCT c nstruction make the tube impervious to corrosion and resistant to chemicals used in treatment of oil and gas wells.

Based on the performance of prototype specimens constructed and tested to date, the service life potential of CCT is substantially longer than that of conventional HSLA steel pipe when subjected to multiple plastic deformation bending cycles with high internal pressure. In addition, CCT is expected to provide the ability t extend the vertical and horizontal reach of existing concentric workover services. This paper reviews the limitations of conventional HSLA steel coiled tubing, explores the design criteria requirements for CCT, and discusses the results of tests performed on numerous CCT prototype specimens.

Introduction

Coiled tubing technology was developed for the purpose of performing workover services in oil and gas wellbores concentric to existing production tubulars. The operational concept of a coiled tubing system involves the deployment of a continuous string of small diameter tubing into a wellbore to perform a specific well service procedure without disturbing the existing completion tubulars and equipment. When the service is completed, the small diameter tubing is retrieved from the wellbore and spooled ont a large reel for transport to and from work locations (Figure 1).

The coiled tubing unit is designed to perform numerous workover services with or without surface pressure present on the well. The primary equipment components which most affect the performance of the tubing string include the injector head, tubing guide, and service reel.

References and illustrations at end of paper

The tubing is deployed into or pulled out of the well with the injector head. The most common design of injector heads in service utilize two opposed-sprocket drive traction chains which are powered by contra-rotating hydraulic motors. These chains are fabricated with interlocking saddle blocks m unted between chain links and machined to fit the circumference of the coiled tubing OD in service. The saddle blocks are forced onto the pipe by a series of hydraulically actuated compression rollers that impart the gripping force required to create and maintain the friction drive system.

The tubing guide is mounted directly above the injector head and is constructed as a 90° arched roller system. The function of the tubing guide is to receive the tubing from the reel and guide it into the chain blocks. The coiled tubing is bent over the tubing guide by applied tension from the reel to ensure that the tubing remains on the rollers. The tubing guide arch is constructed with bend radii generally ranging from 50 inches to 96 inches, depending upon the OD of the coiled tubing in service.

The coiled tubing reel is a fabricated steel spool with a core diameter ranging from 60 to 84 inches and is equipped with a rotating high pressure swivel which allows for continuous fluid pumping services to be performed, even when the pipe is in motion. The reel is equipped with a motor drive system which applies a tension load on the tubing during the service, thereby securing the pipe in the proper orientation on the spool and controlling the pipe motion during the operation.

In the early 1960's, the first coiled tubing string developed for concentric workover purposes was milled from 40 ksi - 50 ksi yield, low-alloy Columbium steel heat treated to produce a minimum full-section yield strength of 69,000 psi. The 15,000 foot strings were constructed by butt-welding 50 foot sections of 1.315-inch OD tubing and spooled onto a service reel with a hub diameter of 9 feet[1]. A number of concentric tubing services were performed with this first coiled tubing string proving the feasibility of the spoolable continuous tube concept for oilfield workover operations.

Concerns for safety and working life of the coiled tubing led the industry in the 1960's to self-impose a maximum working pressure rating of 5,000 psig for the as-rolled 40 - 50 ksi yield HSLA steel. However, when the as-rolled HSLA material yield rating for coiled tubing increased to the 70 ksi range in 1980, the 5,000 psig maximum working pressure limit was not increased correspondingly. This limitation of working pressure provided an added operating safety envelope for coiled tubing work and helped establish th reputation for this concentric workover techn logy as a safe and reliable service.

Since this time, the coiled tubing industry has rapidly grown to provide almost any service which is currently performed with jointed tubing. An estimated 530 coiled tubing units are currently operating worldwide, with available tubing sizes ranging from 3/4-inch OD up to 3-1/2-inch OD.

Performance Limitations of Metallic Coiled Tubing

Coiled tubing services have gained a reputation for safe and reliable service due to a greater understanding of the behavior of the pipe and equipment. However, an inevitable consequence of performing continuous string concentric workover services is the repeated cycling of the tubing into and out of plastic deformation, resulting in the rapid reduction in service life.

The present accepted industry standard for coiled tube material is an A-606 Type 4 Modified HSLA steel with yield strengths ranging from 70 ksi to 80 ksi. The HSLA steel tubing strings used in coiled tubing service undergo bending cycles during deployment and retrieval over radii significantly less than the minimum bending radii needed for the material to remain in the elastic state. The repeated cycling of coiled tubing into and out of plastic deformation induces irreparable damage to the steel tube body.

Figure 2 illustrates the bending cycles the pipe is subjected to when performing any coiled tubing service. The initial state of the tubing is in the spooled condition on the reel. The first bending event takes place when the pipe is pulled off the service reel by the injector head. The hydraulic reel motor resists the pull of the injector head placing the tubing in tension and straightening the primary bend in the pipe. When the pipe reaches the tubing guide, the coiled tubing is bent onto the rollers and around the prescribed radius (bend event 2). As the pipe is pulled into the injector head, the pipe is straightened once again (bend event 3).

These three bending events are repeated in reverse as the pipe is extracted from the well, resulting in a total of six bending events for every "round trip". In general service work, it is common to cycle in and out of the well over short intermediate intervals (drag check, etc.), thus causing greater wear to specific pipe sections.

When coiled tubing is subjected to the aforementioned bending events with internal pressures at or below 25% - 30% of the rated yield pressure for the bending radii commonly used, the tubing accumulates damage and ultimately fails in a condition commonly described as "low cycle fatigue"[2]. Methods are currently available to predict bending cycles-to-failure with reasonable accuracy for isotropic metal tubing strings cycled in this manner with internal pressures.

Many coiled tubing services, however, are performed with internal pressures exceeding 30% of the yield pressure rating of the pipe. As internal pressures increase above the 25% - 30% tubing yield pressure rating, the isotropic steel is subjected to high triaxial stresses imposed by adding pressure t the bending loads, resulting in significant plastic deformation of the pipe. This causes the steel to yield, or creep, at pressures below the rated working pressure of the pipe. The result is the diametral ~rowth of the tube body, commonly referred to as "ballooning".[2,3] When comparing performance of a tubing section with a specific material yield strength and wall thickness cycled over a given bending radii, ballooning is significantly greater for an internal pressure of 5,000 psig than that for an internal pressure of 2,500 psig.

When the tubing experiences ballooning, the average wall thickness of the tube is reduced. Bending imposes tensile and compressive stresses on the pipe, therefore, the stress field is not uniform around the circumference of the tube. As a result, the tube wall thins unevenly about the circumference of the tube. Empirical data obtained from extensive field testing has shown that with a 3% increase in tube body OD, the wall thickness decreases 7.5%, resulting in a loss of burst and collapse pressure rating of as much as 10%. In addition, lab :sting of tubing samples recovered from field service indicated that the material yield strength decreased as a function of usage as well.[4]

The reduced pressure capability of a coiled tubing service string resulting from pipe wall thinning is further complicated by metal loss due to corrosion. Whether corrosion occurs as a result of exposure to the atmosphere or through metal loss from pumping corrosive fluids, additional reductions in wall thickness through pitting significantly decrease the pressure and tensile load rating of the tubing.

The aforementioned consequences to working coiled tubing with high internal pressure established an industry attitude that multiple cycling of coiled tubing strings at lower pressures affords a higher degree of reliability and increases the service life of the pipe. Although services have been performed with 70 ksi and 80 ksi HSLA coiled tubing strings at internal pressures exceeding 5,000 psig, the services were "job specific" and the dramatic effects of ballooning resulted in an accelerated retirement schedule for the tubing string.

Since the internal pressure applied to the tubing will vary significantly over the service life of the pipe, accurate prediction of the cycles-to-failure will most likely require the use of sophisticated numerical models which rely on detailed)nsite monitoring programs designed to evaluate all of th operating conditions of the pipe while in service.

An additional limitation of HSLA steel coiled tubing strings is the practical maximum working depth in highly deviated and horizontal boreholes due to the effects of weight and drag on the pipe. Coiled tubing strings tapered with progressively thicker pipe wall segments towards the surface are designed to provide the highest strength-to-weight ratio possible for work at depths greater than 16,000 feet. However, the ability to transmit coiled tubing strings into horizontal wellbores is also constrained by borehole geometry, weight of the pipe and tools mounted on the end, wellbore pressure, and the frictional effects of the tube length rubbing against the casing and open hole wall.

Alternatives to Conventional Carbon Steel Coiled Tubing

In an attempt to improve the performance capability of coiled tubing, numerous alternatives to conventional carbon steel materials have been explored. One effort underway is the development of higher strength steel materials, such as 100 ksi yield HSLA steel. The higher strength afforded by the 100 ksi material provides a greater pressure rating capability with reduced yield-to-weight ratios and high resistance to sulfide stress cracking.

Coiled tubing strings constructed of titanium are also being developed in an attempt to obtain a high-strength, low-weight product. Titanium offers the ability to increase material yield strengths with a significant reduction in weight as compared to comparable sizes of HSLA steel tubing. Although titanium is resistant to corrosion from H_2S, CO_2, and inhibited HCl acids, rapid general corrosion and etching occurs when titanium is exposed to HF acid[5]. Even with inhibitors added to the acid system, the rate of titanium metal loss dissolved in the presence of HF acid is unavoidable, effectively eliminating it as a candidate for use in performing HCl - HF acid stimulation treatments.

Although the aforementioned high strength metallic materials are expected to expand the service envelope of coiled tubing relative to conventional HSLA steel, these materials will still be subjected to bending cycles, plastic deformation, and ultimate fatigue failure due to the repeated high strains imposed by bending with internal pressure.

An alternative material which promises to overcome the limitations of metallic materials for the construction of coiled tubing can be found in composites. Fibrous composite materials can be tailored to exhibit unique anisotropic characteristics to optimally address burst and collapse pressures as well as tensile and compression loads. The results of an investigation to study the potential f composite materials to improve the performance of coiled tubing is presented in the remainder of the paper.

Background and Discussion of Composite Materials

Composite materials are composed of high strength elements (usually small diameter fibers) which are normally locked into a preferred orientation by a surrounding matrix material. The matrix material, normally much weaker than the fibers, serves the critical role of transferring load into the fibers. With composites, fundamental design principles can be used to tailor the strengths and stiffnesses in different directions of the structure. The resulting properties of a composite material are anisotropic and the load-deformation response is tractable using the principles of composite mechanics.

The fibers which have the highest potential for application in constructing CCT include glass, carbon, and Kevlar®. The matrix materials available can range from thermoset and therm plastic polymeric resins to metals. Thermoset resins such as epoxies are readily available and easy to process, making them the likely selection for first generation CCT product development.

High performance composite structures are generally constructed as a build-up of laminate layers with the fibers in e layer oriented in a particular direction (or directions w... a fabric or braided construction is used). For analysis and design purposes, the material properties normally used are for a ply of material in which the mechanical properties for the layer are resolved into principal directions. For a unidirectional ply, the axis parallel to the fiber and transverse to it are the principal directions.

Also note that with composites, it is usually more descriptive to characterize the structures resistance to load in terms of strain rather than stress. The stress in the tube wall is an averaged property based on the cross-sectional area of the tube whil the local stress can have wide variance for different lamina (layer) within the cross-section. This occurs because of the anisotropic properties of the lamina and the fact that each layer has strength and stiffnesses in the fiber direction several times the corresponding properties measured in the transverse direction.

A listing of typical mechanical properties for unidirectional laminates in an epoxy matrix for several materials is presented in Table 1 and representative stress-strain curves for unidirectional laminates can be compared in Figure 3.

E-glass laminates are the least expensive of the aforementioned fiber materials which makes this fiber desirable on a unit cost basis. S-glass laminates have slightly higher moduli and strength properties as compared to E-glass. In addition, S-glass fibers are more resistant to industrial chemicals than E-glass fibers, but the cost for S-glass is approximately five times greater.

The properties shown in Table 1 for carbon laminates are typical for the commodity type material used in applications ranging from sporting goods to aircraft. Carbon fibers provide the highest axial strength and moduli and yield a near zero coefficient of thermal expansion in the axial direction. The cost of carbon fiber with properties similar to those seen in Table 1 is approximately twice that of the S-glass fiber. There are many different carbon fibers available in the industry with strengths and axial modulus values up to five times greater than those shown in Table 1. However, the cost of high performance carbon fibers can be up to several times greater than commodity grade carbon fibers.

Kevlar® fibers are noted for their damage tolerant characteristics and can be purchased for approximately the same cost as commodity grade carbon fibers. The Kevlar® 49 material described in Table 1 has a modulus in the fiber direction approximately fifty percent greater than that of S-glass fiber and approximately half that of the carbon material.

One important criterion in selecting the appropriate material for CCT construction is the "strain-to-failure" of the unidirectional laminate. The ultimate strain values for unidirectional laminates presented in Table 1 are typically lower than the corresponding values for the fibers without resin. S-glass fiber laminates have the highest strain-to-failure (2.3% - 2.9%) with carbon fiber laminates exhibiting the lowest (1.5%). The ultimate strain for the Kevlar® fiber laminate is approximately 2%. High performance carbon fiber are also available which provide a strain-to-failure of approximately 2%, but as noted above, the cost is substantially greater. Kevlar® fiber laminates with higher strain-to-failure are also available, but the material exhibits a lower fiber direction modulus.

As noted above, an epoxy matrix material represents the best combination of performance properties and cost when designing CCT for various applications. Common epoxies are resistant to most chemicals used in treating oil and gas wells and can operate in temperatures ranging from 225°F to 350°F. Higher temperature resins including bismaleimide and thermoplastic resins such as PEEK can also be used in CCT construction, but at a cost substantially higher than that for epoxy.

Prototype CCT Development and Design Considerations

Fabrication Processes

There are three principal candidate processes (pultrusion, filament winding, and braiding) available for fabricating continuous composite tubular products. A brief description of each is presented below.

Pultrusion is a process in which fibers are drawn from spools into a specially shaped die designed to form the product into the desired cross-sectional geometry. The resin can be introduced as the fibers are drawn through a vat of resin just before the fibers enter the die or alternatively applied under pressure inside the die. The resin is cured rapidly, usually by the application of heat, as it traverses through the short length die. The product is pulled from the die by a set of reciprocating gripper blocks.

Continuous Process Filament Winding is a manufacturing process where spools of fiber are mounted on so called "ring winders" which rotate around the pipe to deposit the composite material. Conventional short length filament wound pipe is produced by rotating the pipe in successive clockwise and ...ter-clockwise directions with the speed of rotation and the ... of material feed determining the orientation of each lamina layer. Rotation in both clockwise and counter-clockwise directions is impractical for continuous pipe, so separate ring winders are required to apply each lamina in the proper orientation. Resin can be applied to the fibers in a wet bath arrangement or prepregnation stands with the resin already applied may be used.

Braiding is a well established process for making semi-continuous products[6]. In braiding, the strands of fibers are usually fed in the direction of braid formation and interlace each other to form a tube. Circular braiders have been used for many years to reinforce flexible pressure hoses, and their selection for use in reinforced composites is a natural extension of this application. In a simple circular braider, the carriers move in a serpentine manner around a circular track, half of the carriers moving in each direction. The strands cross paths frequently to yield interlacing patterns and they close t form a tube. Axial yarns supplied from spools remote to the braider may be integrated into the braid to provide increased axial stiffness and strength. A braided structure can be made noncircular as well as circular and the cross-section may vary along the length. A schematic of circular braider equipment is presented in Figure 4. Resin is usually applied to the strands by soaking them in resin just prior to the completion of braiding.

CCT Development History

In 1988, Conoco initiated a project to explore the potential application of composite materials for the construction of high pressure, long length non-corroding tubulars for use as onshore water injection lines. After investigating the requirements, it was anticipated that such a product could be designed and produced by one of the low-cost, volume production processes discussed above.

In 1989, several hundred feet of pultruded fiberglass composite pipe was fabricated and spooled onto a nine-foot diameter reel. Although the ability to design and fabricate composite pipe which resisted structural damage due to spooling was demonstrated, maintaining a pressure seal within the pipe was found to be a difficult challenge. An alternative approach incorporating an internal liner was therefore pursued. In addition to sealing, the liner also served as a mandrel for fabrication of the tube. The separation of the sealing and structural functions using a liner over which is constructed a structural composite wall was successfully accomplished in subsequent develop work using both the filament winding and braiding processes.

In 1989, a contract was awarded a Norwegian company to develop a spoolable composite pipe for small diameter subsea lines. This successful development effort is reported in references 7 and 8.

A United States centered effort to fabricate and test composite coiled tubing was initiated in 1989 and has continued to the present. The results reported in the CCT Test Results section are for specimens designed by Conoco and fabricated in the U.S. on contract using the braiding method of construction.

CCT Design Considerations

CCT provides several potential improvements and new enabling capabilities compared to conventional steel coiled tubing. Each of the commonly recognized advantages of composites (reduced weight, corrosion resistance, resistance to fatigue, etc.) will provide an important advantage in making coiled tubing operations safer and more productive by extending the operational range of depth and allowable working pressure.

The primary problem with metal coiled tubing as discussed above is that the high strains imposed by spooling and internal pressure cause the pipe to deform plastically resulting in reductions in the tube wall thickness and increased diameter. Both the reduced wall thickness and the larger diameter increase the stress level for succeeding cycles resulting in progressively greater reductions in wall thickness and larger diameters eventually culminating in the failure of the pipe. At high pressures, failure can occur after only a very few cycles as was discussed earlier.

In CCT design, one of the most important constraints is that the allowable fiber strain not be exceeded. Typically, the strains imposed on coiled tubing are much higher than are the strains applied to aircraft or spacecraft primary structures. For example, the maximum strain imposed on commercial aircraft wings (most heavily loaded component) ranges from 0.0045 to 0.0055. In comparison, the axial strain imposed by winding 1.5-inch OD coiled tubing onto a six-foot diameter spool is 0.020. When the additional strains due to internal pressure and tension or compression loads are superimposed, the resulting strain acting on the coiled tubing body can become very high.

The strain allowables for a unidirectional lamina (Table 1) show that placing fibers in the axial direction will result in strains for coiled tubing which either exceed or closely approach the ultimate strain capability of most high-performance fibers. For offshore applications, it may be practical to use large diameter spools, thus opening the latitude of design options. However, to meet practical maximum diameter spool requirements established by onshore transportation constraints (bridges, tunnels, etc.), it is necessary to eliminate or at least limit the amount of fiber o-ented parallel to the axis of the tube and tailor the design to a stiffness and strength properties in other ways.

Insight concerning how one might structurally tailor a composite tube cross-section to accomplish high strain perf rmance is suggested by composite mechanics research conducted by the National Aeronautics and Space Administration[9,10]. These studies demonstrated that certain laminate constructions, namely cross-plied laminates with fiber angles f from ±35 to ±55 to the direction of the high strain can be loaded to impose very high strains (in excess of 0.030) without failing. In addition, it is a well know fact that the optimal cross-ply fiber orientation for a tube design to carry pure pressure is ±55. This information suggests that much of the material in the cross-section should be oriented with cross-ply angles of from ±35 to ±55 to the axis of the tube.

The stress-strain response for ±45 cross-ply laminates at high strains is nonlinear adding certain complexity to the design. High strains are permissible for a cross-ply laminate because the strain in the fiber direction is reduced to a fraction of the strain in the axial direction. The magnitude of this effect is illustrated in Figure 5 in which the mechanical properties (modulus, Poisson's ratio and coefficient of thermal expansion) are presented for a cross-ply laminate constructed of carbon/epoxy.

Increasing the cross-ply angle also affects the other mechanical properties, most notably, there is a significant decrease in the axial stiffness. The lower axial stiffness translates into lower ultimate strength and also reduces the critical helical buckling load of the tube in response to axial compressive loads as the tube is laterally restrained by the casing or open hole.

Therefore, the design of composite tubing (i.e., the thickness and orientation of the fibers within the tubular wall) is an optimization process in which all the imposed loads and requirements must be consistent with the candidate material's characteristic properties. In the present study a computer code was developed to study the design variables and to produce representative designs for prototype fabrication and testing.

The second technology insight provided is derived from NASA studies of the energy absorbed and the failure mechanisms for a composite tube dynamically loaded by crushing the tube between two platens[11]. These studies showed that certain materials and constructions afforded composite tubes better energy absorption than metal tubes. The highest energy absorption recorded was associated with carbon. Following failure, however, the most efficient all-carbon tubes were essentially reduced to a pile of broken fibers. In comparison, Kevlar® tubes absorbed less energy, but the tube remained intact following collapse. Hybrid tubes constructed of combinations of Kevlar® and carbon also exhibited this structural continuity feature. The implication for CCT is that a tube constructed of Kevlar® fiber will probably exhibit better damage tolerance and structural continuity following damage or local failure than tubes constructed of all carbon or glass. This ability of Kevlar® tubes to hinge and weaken but not fail is a feature which may permit the tubing string to be retrieved from the hole without fishing following downhole damage.

The mechanical properties for ±45 cross-ply laminates constructed of E-glass/epoxy, S-glass/epoxy, carbon/epoxy and Kevlar®/epoxy using the unidirectional laminate properties listed in Table 1 are presented in Table 2. It is interesting to note that even though the unidirectional modulus in the fiber direction for a Kevlar® 49 fiber laminate is 69-percent higher than for the E-glass fiber unidirectional laminates, the axial modulus of the Kevlar® ±45 laminate is less than half the axial modulus for the ±45 glass laminates. The unidirectional laminate of E-glass has a shear modulus approximately 2-2/3 times the value for Kevlar® 49. This comparison illustrates the important influence the shear modulus of the unidirectional laminate has on the axial stiffness of a ±45 cross-ply laminate.

CCT Prototype Test Results

Several CCT specimens were fabricated of E-glass/epoxy, S-glass/epoxy, carbon/epoxy, and Kevlar®/epoxy materials using pultrusion, filament winding and braiding processes. The test data discussed in this paper, however, will concentrate only on specimens constructed of Kevlar®/epoxy fabricated using the braiding fabrication process. As discussed above, this combination of material and construction process is expected to provide excellent durability and damage-toleran' performance properties.

One design approach to permit CCT to carry high pressure as well as high axial bending strain without over straining the fibers is to place most of the fibers in the cross-section oriented at an angle greater than 30° relative to the axis of the tube. The CCT test data reported herein are for 1.50 inch OD (1.00 inch ID) Kevlar®/epoxy tubes constructed with cross-ply angles of approximately ±45. The design constraints for the CCT specimens are presented in Table 3.

Static Pressure Testing

;s strain imposed on a CCT specimen as a function of internal pressure is presented in Figure 6. The circumferential strain corresponding to an internal pressure of 5000-psig is approximately 0.008. Axial gages on opposite sides of the tube registered a negative strain of approximately 0.003. The contraction of the tube under pressure is a consequence of the negative Poisson ratio for a ±45 laminate.

Bending Tests Without Pressure Applied

A 1.00-inch ID (1.50-inch OD) specimen was subjected to 50,000 bending cycles (without internal pressure applied) in the same direction using the three point bend test apparatus shown in Figure 7. The equivalent bend radius-of-curvature specified for the test was 29 inches and a strain gage mounted on the tension side of tube registered a maximum strain of 0.026. The tube specimen retained a slight residual curvature following the bending tests (Figure 8) but could be reverse bent to straighten it. The tube was then subjected to internal pressure loading until it burst at a pressure of 19,486 psig.

A series of bending cycles were imposed upon another CCT specimen using a four-point bend test apparatus. The spacing between load application points was 22-inches for the bottom set of loads and 8-inches f r the top set of loads. The strain r three cycles f ±0.5-inch, ±.75-inch, ±1-inch, and ±1.25-inch cross-head displacement are shown in Figure 9. These displacements correspond to bending the tube to an equivalent radius of curvature of 90, 57, 42, and 33-inches, respectively. The strain gages ceased to function during the latter phase of the tests, however, strains of 0.022 in the axial direction and 0.019 in the circumferential direction were measured for the 1.25-inch displacement.

Bending Tests With Pressure Applied

Several tests were conducted to assess the effect of combined bending and pressure on the performance and failure of CCT specimens. These tests were conducted using a four-point bend test apparatus with internal pressure applied to the specimen during cycling. The performance for several of the CCT specimens is presented in Figure 10. The number of cycles is plotted as a function of the internal pressure load within the tube while subjected to a bending displacement equivalent to a 6.5-foot diameter spool. Also presented for comparison is data for 70-ksi yield steel coiled tubing obtained from reference 2. Star symbols for the CCT indicate that the specimens failed under these test conditions. The square symbols indicate that the specimens did not fail during the test procedure. Data presented with a line connecting the stars and squares indicate the test was first conducted at the lower pressure and resumed at the higher pressure for the duration of the test.

The data indicates for a test condition of combined pressure and bending that the CCT specimens performed orders of magnitude better than 70 ksi yield HSLA steel tubing in the number of cycles the tubing can endure prior to failure. The data also suggests a capability to repeatedly deploy CCT at pressures which are well beyond the accepted safe performance range of steel coiled tubing. One test specimen failed after 81,514 cycles in which 10,000 psig internal pressure was held during the cycling procedure.

CCT Tension and Compression Tests

CCT specimens were loaded in axial tension and compression using a Material Test System (MTS) machine with hydraulic grips. Metal inserts were placed inside the tubes at the ends to permit large gripping forces to be applied, thus providing the 42-inch long specimens with essentially "clamped-end" boundary conditions. A plot of the tension and compression response for a ±45 Kevlar® tube specimen is presented in Figure 11. The specimen was loaded to 9,060-lb in tension and 1,725-lb in compression. The modulus of elasticity for the initial portion of the curve is measured to be approximately 1.10 million psi which is in agreement with the analytical prediction presented in Table 2. The response is highly nonlinear for tension strains above 0.8%.

As discussed above, the presence of uniformly distributed, axially oriented fibers in the cross-section can severely limit the radius of curvature to which the tube can be bent. One variation studied in the present investigation to increase the axial stiffness of the tube (consistent with the strain limitations of axial fiber) was to place the axial fibers in the cross-section selectively to minimize the effects of bending. In this configuration, the high stiffness, axially oriented fibers are clustered in the tube cross-section at 90° and 270° positions, creating a significantly different major and minor principal moment of inertia[12]. Like the buckling of a yardstick in response to an axial load, the tube automatically chooses to bend about the minor moment of inertia and thus imposes only small bending strains on the axial fibers.

The selective axial reinforcement feature was incorporated in the [±45/0] CCT for which the load-strain response is shown in Figure 11. The ±45 oriented material of the tube is Kevlar® while the axial [0] material is carbon fiber. The carbon fiber constituted only 7% of the cross-sectional area of the tube structural wall. As can be seen, the addition of this small amount of axial carbon fibers significantly stiffened the cross-section and provided a linear response in tension to 00-lb and in compression to 3,250-lb. The axial modulus o specimen is approximately 1.95 million psi, an increase f 77% over the design without axial carbon fibers. The tube did not buckle under the compression load even with the long unsupported length nor did it fail in tension. These tests show that CCT can be designed to carry the compressive loads typically imposed by the injector head driving the tube through the stripper block.

CCT Collapse Pressure Test

CCT must be capable of operating under external as well as internal pressure. CCT specimens with sealed ends were placed in a pressure chamber to study external collapse effects. Preliminary results indicate that CCT can be designed to meet the collapse resistance conditions specified in Table 3.

CCT Deployment Tests

Based on t_ confidence developed from laboratory tests, a field test of CCT was conducted. The purpose of the test was to determine how the CCT would perform when bent over a conventional tubing guide and run through a conventional injector head and stripper assembly while maintaining 2,500 psig internal pressure. A 20-foot section of CCT was connected to a section of 70 ksi yield, A606 Type-4 modified A steel coiled tubing spooled ont a conventional 72-inch diameter service reel. The composite section was positioned in the injector head equipped with standard 1.50-inch chain blocks. A 50-inch radius tubing guide arch was used, equipped with eight standard polyurethane rollers along the primary 90° arch and three rollers for containment from above.

The downhole end of the composite tubing was attached to a 10-foot long section of steel tube which served to guide the pipe through the stripper blocks and into the unpressurized test well. The unsupported distance between the lowest containing chain block and the top of the stripper assembly was measured to be 12-inches. The back tension for the tubing string was supplied by the coiled tubing reel.

The test procedure involved pressurizing the 20-foot section of CCT to 2,500 psig and working approximately 11 feet of the tube back and forth over the tubing guide arch, through the chain drive, and into the stripper assembly. The steel coiled tubing run from the reel to the CCT section was only used to provide tensile force on the sample and was not subjected to any internal pressure.

After 760 trips, the steel coiled tubing broke on the reel and the test was continued by placing a weight on the end of the CCT to maintain the bend orientation on the tubing guide arch support. A total of 1500 trips into and out of the injector head was performed (3,000 bending cycles) while maintaining an internal pressure of approximately 2500-psig (±100-psig) without failure of the CCT specimen. This is approximately 5-times the similar life expectancy for steel coiled tubing.

Through out the 1,500 cycle test program, the inside chain pressure acting against the CCT was zero. After the 1,500 cycles were obtained, additional trip cycle tests were performed with varying amounts of internal CCT pressure while imposing 300 psig and 500 psig inside chain pressure onto the CCT body. These inside chain pressures correspond to normal load forces of 530 lb_f and 880 lb_f, respectively. For both of the inside chain pressures identified, the CCT specimen was cycled through the injector head five times at an internal pressure of 2,500 psig, five times at an internal pressure of 1,200 psig, and five times at zero psig internal pressure. The CCT was then repressurized to 2,500 psig and held for 30 minutes.

Visual inspection upon completion of all tests showed that the CCT outer laminate exhibited wear in the vicinity of the coupling termination which was upset to 1.660 inches. However, there was negligible damage or wear to the remainder of the CCT outer body surface as a result of the concentrated loads and forces applied by the chain drive blocks.

Prior to trip cycling the CCT specimen, 11 specific locations were marked on the outer diameter of the tube body (top and 90° orientation) at one foot increments. Micrometer measurements were taken at the aforementioned 11 points on the CCT OD with zero psig internal pressure and when pressurized to 2,500 psig. Additional micrometer readings were taken after 500 and 1,500 trip cycles, while pressurized to approximately 2,500 psig. All measurements taken remained within 0.020 inches of original pre-test, unpressurized tube OD measurements.

The 20 foot CCT specimen, designed for 5,000 psig operating pressure, was returned to the lab and pressurized to 9,100-psig without failure. At 9,100 psig internal pressure, a small leak developed at the couplings and the low volume pump used was unable to increase the pressure, terminating the test.

CCT Shear Cut Tests

Shear tests were conducted on CCT using conventional coiled tubing shear ram blades available within the oil service industry. Numerous sections of CCT specimens were sheared in a 3.06-inch ID opposed-ram test fixture and the severed ends were evaluated for quality of cut and body integrity. In all cases, the sheared CCT sections maintained full body geometry and laminate integrity with shear pressures several times less than comparable sizes of 70 ksi yield HSLA steel coiled tubing. Following these tests, additional development w rk was performed on conventional shear blades and subsequent shearing tests indicated a marked improvement in cut surface condition.

Potential Advantages and Enhanced Service Ability of CCT

CCT has the ability of providing enhanced service in all areas of coiled tubing operations presently defined. The specific areas in which CCT can make a significant impact within the coiled tubing service industry (as compared to the current coiled tubing materials) are discussed below.

1. Pressure Service

HSLA steel tubing has a limited pressure-cycle lifetime when subjected to plastic deformation events inherent to coiled tubing service operations. Due to the anisotropic nature of CCT, tube body axial and hoop strengths can be tailored independently. Therefore, burst and collapse pressure resistance can be enhanced through fiber orientation without increasing wall thickness as normally seen with isotropic metals. This directly translates into working pressure ratings for CCT two - three times that of HSLA steel.

2. Corrosion Resistance

Because CCT can be constructed of corrosion resistant materials, acid services can be pumped without the need for corrosion inhibitors to protect the tubing. The reduction or elimination of these tenacious inhibition chemicals can reduce induced damage to the formation presently considered unavoidable. In addition, CCT can be made impervious to impregnation by H_2S and CO_2. This makes CCT a desirable alternative to corrosion resistant alloy tubulars for permanent tubing installations. In addition, the continuous CCT string will eliminate the need for premium connections along the tube body, further enhancing its economic and environmental advantages.

3. Design for Purpose

In general, CCT is constructed with multiple layers f materials such as carbon, glass, and/or Kevlar® fibers according to the various strength requirements of the tube. However, not all layers are structural. For example, an exterior coating with high wear-resistant properties can be incorporated into the CCT design to provide enhanced protection of the structural fibers and also provide reduced frictional drag coefficients for the tube.

The internal liner can be constructed of materials such as nylon, polyethylene, and polytetrafluoroethylene compounds creating an internal barrier impervious to the fluids pumped. In addition, the aforementioned liner materials offer a lower frictional coefficient to fluid flow, thereby minimizing pressure loss through the CCT when implementing pumping services.

Because CCT is constructed of non-metallic materials, conductive wires can be embedded or inlaid within the laminates along the length of a "Smart CCT" string. Power can be provided to downhole tools through electrical conductors within the tube body and real time communication can be transmitted to surface either through electrical wires or fiber optic cables. The elimination of the internal armored cable dramatically enhances the utility of CCT, allowing real-time monitoring of downhole stimulation services. This enabling capability has the potential to provide significant improvements in logging and monitoring downhole conditions, resulting in improved treatment and production data acquisition.

4. Tube Weight

HSLA steel coiled tubing is limited to a finite distance in which it is capable of transporting tools along the lateral borehole for a given set of borehole criteria. Depending upon the material selected for construction of the tube, the weight per foot of CCT can be from 25% to 40% that of equivalent sizes of HSLA steel coiled tubing. When coupled with an outer body coating constructed from a material possessing low frictional coefficients, the ability t transport CCT deep into deviated and lateral boreholes will be many times greater than is currently possible with an equivalent size of HSLA steel coiled tubing.

The weight reduction can be further enhanced by displacing the CCT with a relatively lighter fluid or gas such as nitrogen, thereby "neutrally buoying" the tubing string. Coupled with floatation devices on the downhole tool assemblies, the maximum lateral extent CCT can be transported is significantly increased.

5. Improved Service Life

CCT can withstand a significantly greater number of bending cycles than conventional HSLA steel coiled tubing. Based on the experience and test data obtained, CCT has demonstrated the capability of exceeding HSLA steel tubing service life by a factor of ten or more.

In addition, CCT behaves differently from HSLA steel coiled tubing when subjected to bending events of the magnitude seen in normal coiled tubing service. By design, bending strains imposed upon CCT do not result in plastic deformation to the degree experienced by isotropic metals. One can expect minimal diametral growth, if any, following extensive use.

6. Enhanced Safety

Of greatest concern to the operator in implementing concentric servic - utilizing coiled tubing is the ability to perform the prescribed service safely and effectively. The aforementioned benefits to the use of CCT clearly indicate that a significantly greater "performance & safety envelope" is available when compared with HSLA steel coiled tubing strings.

The expanded range of pressure and bending cycle service allows the operator the opportunity to safely perform high pressure work r to dramatically extend the life of the work ing when implementing conventional services.

Future Advancements In Composite Coiled Tubing

The test data indicates that a composite tube can be designed and fabricated which is capable of overcoming the limitations associated with the plastic behavior of steel coiled tubing subjected to high pressures and repeated small radius bending. There is much work still to be done, however, to understand the capabilities and limitations of CCT. Advanced materials may permit extending the operational temperature range and chemically resistant liner materials could permit expanding the capability to transport high concentrations of acids and bases. Termination technology to seal CCT at very high pressures is another technology needing further development. Also the effects of damage by wear and impact need further assessment.

CONCLUSIONS

1. HSLA steel coiled tubing strings have a limited service life dependant upon the amount of internal pressure and bending cycles imposed upon the string.

2. The feasibility of constructing composite tubulars capable of being spooled onto and deployed through conventional coiled tubing equipment has been demonstrated.

3. Composite materials can be tailored to provide properties unavailable with metals such as high fatigue life, minimal diametral growth, and reduced weight.

4. Composite coiled tubing can be designed to meet spooling and high combined load imposed on high performance coiled tubing.

5. Composite coiled tubing provides the opportunity to expand the application opportunities to higher operating pressure and longer reach in horizontal and deviated wells.

6. Advanced low-cost manufacturing methods permit composite components to be produced at competitive prices.

ACKNOWLEDGEMENTS

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SI METRIC CONVERSION FACTORS

foot	x	3.048	E-01	=	m
inch	x	2.54	E+00	=	cm
lb_f	x	4.535 924	E-01	=	kg
psig	x	6.894757		=	KPa

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Table 1.

	E-Glass /Epoxy	S-2 Glass /Epoxy	Carbon /Epoxy	KEVLAR® 49 /Epoxy
Axial Modulus, Msi	6.5	8.0	21	11
Axial Strain to Failure, %	2.3	2.9	1.5	1.9
Transverse Modulus, Msi	1.8	2.5	1.5	0.80
Shear Modulus, Msi	0.80	0.90	0.90	0.30
Poisson Ratio, (Axial-Transverse)	0.25	0.26	0.28	0.34
Density, lb/cubic inch	0.75	0.72	0.57	0.50

Typical Mechanical Properties for Various Unidirectional Laminates in an Epoxy Matrix at 60% Volume Fraction.

Table 2.

	E-Glass /Epoxy	S-2 Glass /Epoxy	Carbon /Epoxy	KEVLAR® 49 /Epoxy
Axial Modulus, Msi	2.38	2.77	3.12	1.09
Transverse Modulus, Msi	2.38	2.77	3.12	1.09
Shear Modulus, Msi	1.88	2.35	5.44	2.84
Poisson Ratio, (Axial-Transverse)	0.49	0.54	0.73	0.82
Axial Coef. Thermal Expansion, Microstrain/°F	6.95	7.37	0.92	0.77

Mechanical Properties for [+-45/-+45] Cross-Ply Laminates in an Epoxy Matrix.

Table 3.

CCT SPECIFICATIONS

1. 1.0-inch I.D.
2. 1.5-inch O.D.
3. 5000-psig Operating Pressure
4. 2000-lb Axial Compression
5. Tension: 1.5 x Air Weight/Unit Length x Length
6. 1500-psig Collapse Resistance
7. 180° F Maximum Operating Temperature
8. 7-ft. Minimum Diameter Spool
9. Minimum of 2500 Bending Cycles
10. Smooth, Tough, Abrasion Resistant Interior and Exterior Surfaces
11. Simultaneous Loads: 3+4, 3+5, 3+8
12. Damage Tolerant
13. Producible in 10,000-ft. Lengths

Preliminary Design Specifications for Initial CCT Prototype Specimens.

SPE265 7'

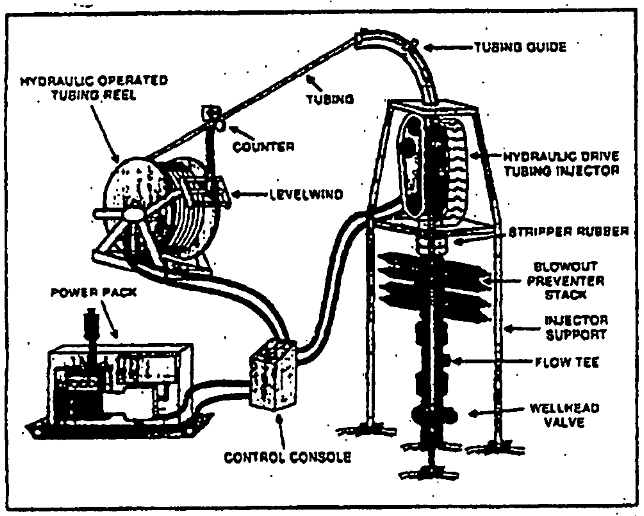

Figure 1. Mechanical Elements of a Hydraulic Coiled Tubing Unit.

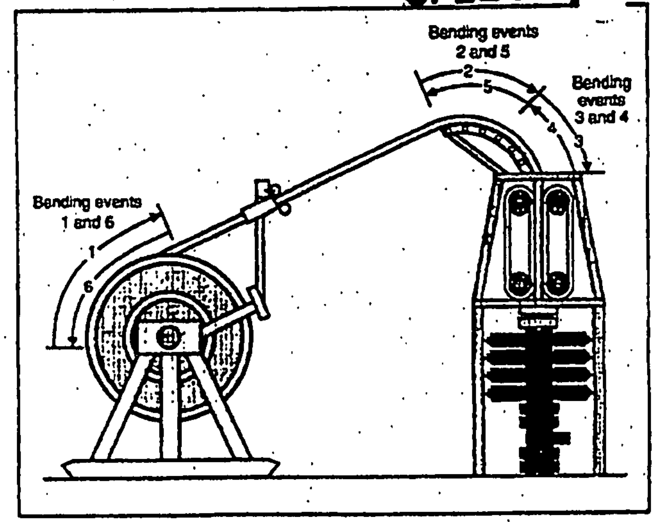

Figure 2. Illustration of Bending Events Which Occur When Running Coiled tubing In and Out of the Wellbore.

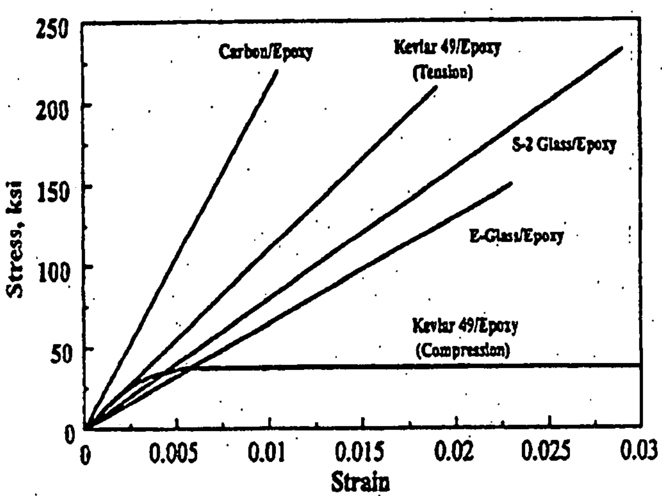

Figure 3. Unidirectional Laminate Stress vrs. Strain Response for Carbon/Epoxy, Glass/Epoxy, and Kevlar®/Epoxy Composites.

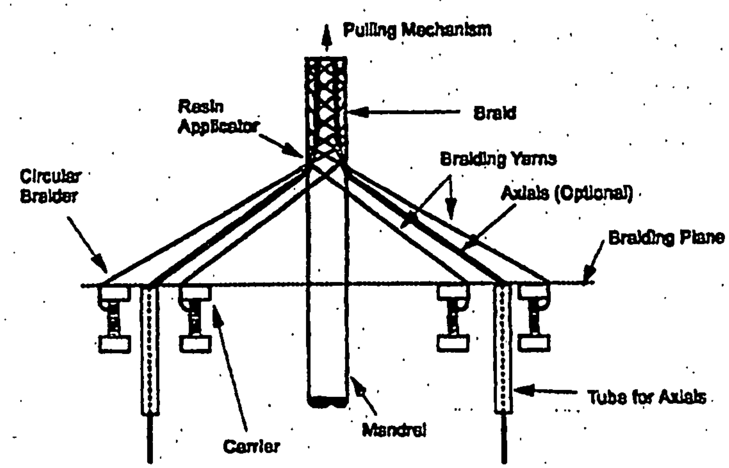

Figure 4. Schematic of a Circular Braider Used in Constructing CCT Prototype Specimens.

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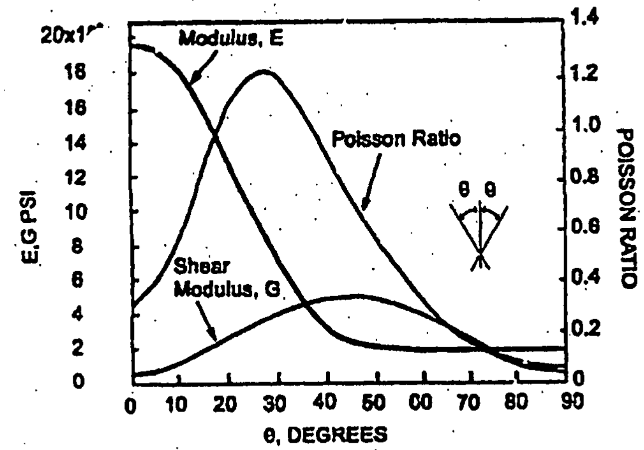


Figure 5. Elastic Properties For A Cross-Ply Laminate Constructed of Carbon in an Epoxy Matrix.

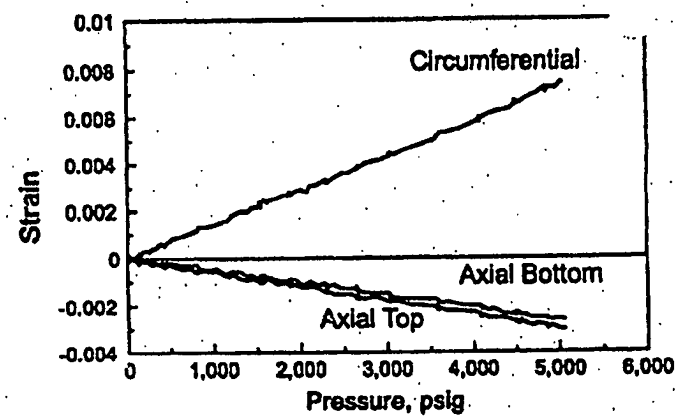


Figure 6. Strain Imposed on a Kevlar®/Epoxy Tube Specimen as a Function of Internal Pressure.

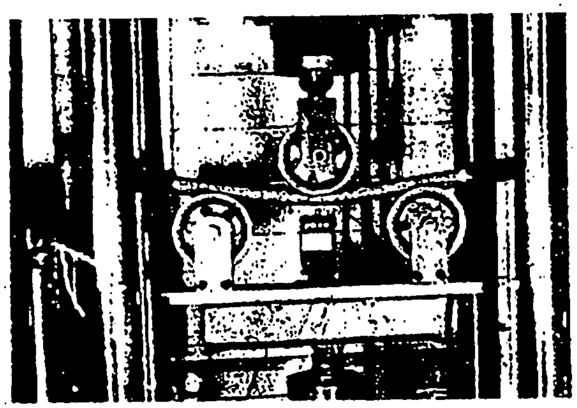
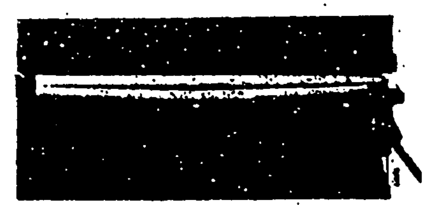


Figure 7. Three-Point Bending Test Apparatus Initially Used to Cycle Test CCT Specimens.



a. Curvature Caused By Bending

b. Pipe Straightened By Reverse Bending

Figure 8. Residual Bend and Straightening Effects on Test CCT Specimens.

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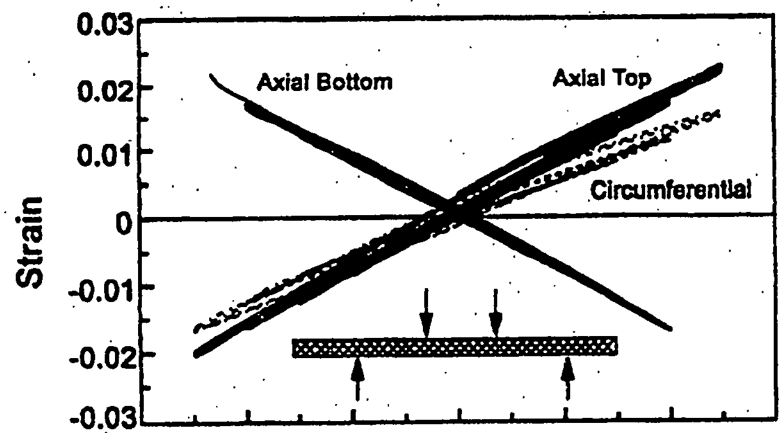

Figure 9. Strains Recorded For Three Bending Cycles of Cross-Head Displacement of Kevlar® CCT Specimens.

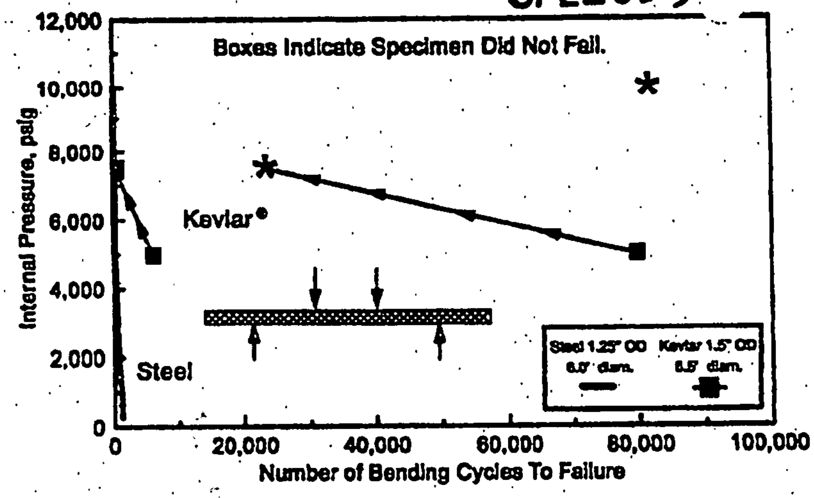

Figure 10. Comparative Analysis of Bending Cycles at Constant Pressure for Steel and Composite CT.

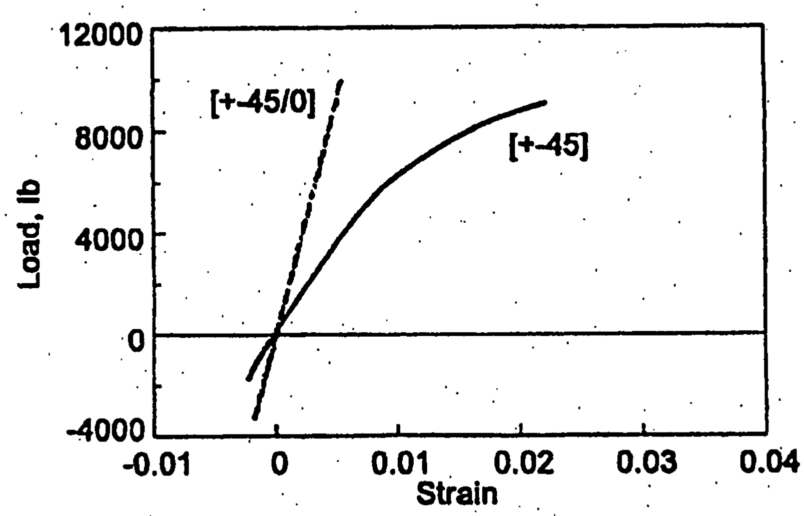

Figure 11. Tension and Compression Response for Kevlar® CCT Specimens.

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